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Polarization Studies of the Venus uv Contrasts: Cloud Height and Haze Variability[1]

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Polarimetry is able to show direct evidence for compositional differences in the Venus clouds. We present observations (collected during 2½ Venus years by the Pioneer Venus Orbiter) of the polarization in four colors of the bright and dark ultraviolet features. We find that the polarization is significantly different between the bright and dark areas. The data show that the "null" model of L. W. Esposito (1980, *J. Geophys. Res.* **85**, 8151–8157) and the "overlying haze" model of J. B. Pollack *et al.* (1980, *J. Geophys. Res.* **85**, 8223–8231) are insufficient. Exact calculations of the polarization, including multiple scattering and vertical inhomogeneity near the Venus cloud tops, are able to match the observations. Our results give a straightforward interpretation of the polarization differences in terms of known constituents of the Venus atmosphere. The submicron haze and uv absorbers are anticorrelated: for haze properties as given by K. Kawabata *et al.* (1980, *J. Geophys. Res.* **85**, 8129–8140) the excess haze depth at 9350 Å over the bright regions is $\Delta\tau_h = 0.03 \pm 0.02$. The cloud top is slightly lower in the dark features: the extra optical depth at 2700 Å in Rayleigh scattering above the darker areas is $\Delta\tau_R = 0.010 \pm 0.005$. This corresponds to a height difference of 1.2 ± 0.6 km at the cloud tops. The calculated polarization which matches our data also explains the relative polarization of bright and dark features observed by Mariner 10. The observed differential polarization cannot be explained by differential distribution of haze, if the haze aerosols have an effective size of 0.49 μm, as determined by K. Kawabata *et al.* (1982, submitted) for the aerosols overlying the Venus equator. We propose two models for the uv contrasts consistent with our results. In a physical model, the dark uv regions are locations of vertical convergence and horizontal divergence. In a chemical model, we propose that the photochemistry is limited by local variations in water vapor and molecular oxygen. The portions of the atmosphere where these constituents are depleted at the cloud tops are the dark uv features. Strong support for this chemical explanation is the observation that the number of sulfur atoms above the cloud tops is equal over both the bright and dark areas. The mass budget of sulfur at these altitudes is balanced between excess sulfuric acid haze over the bright regions and excess SO_2 in the dark regions.

THE PUZZLE OF THE VENUS ULTRAVIOLET CONTRASTS

Dark markings on Venus visible only in the ultraviolet were first reported by Wright (1927) and Ross (1928). In the following fifty years, these features were studied sporadically from the Earth (Boyer and Camichel, 1961; Smith, 1967; Boyer and Güerin, 1969; Coffeen, 1971; Scott and Reese, 1972; Barker *et al.*, 1975; Dollfus, 1975). Earth-based observations have severe limitations in their resolution in space and time. Small features cannot be seen, and spurious speeds and periodicities can be inferred

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from the undersampled time record (Scott and Reese, 1972; Beebe, 1972). Spacecraft observations from Mariner 10 (Murray *et al.*, 1974; Belton *et al.*, 1976a,b; Anderson *et al.*, 1978) and Pioneer Venus (Travis *et al.*, 1979a,b; Esposito, 1980; Rossow *et al.*, 1980) have removed some of these difficulties. We now have a relatively long-term, unbiased record of the temporal (Rossow *et al.*, 1980), spatial (Belton *et al.*, 1976a; Rossow *et al.*, 1980; Esposito and Gates, 1981), and spectral (Esposito, 1980; hereafter, "Paper I") characteristics of these contrast features.

Despite this broad range of descriptive information, the most important questions about these features are still unanswered. Following the Mariner 10 mission, Young (1975) described the question of the nature of the uv features as "the most frustrating of all." What is the absorber (or absorbers) responsible for the darkening? What are the physical or chemical mechanisms that bring the absorbers selectively into view? Is the same cause responsible for all size features, from kilometers to planetary scale? The behavior of these features has been used to infer both wind speeds (Limaye and Suomi, 1981; Rossow *et al.*, 1980) and the existence of planetary waves (Belton *et al.*, 1976b; Covey and Schubert, 1981). Are these inferences valid? Further, if the large-scale contrasts are associated in some way with waves, do the markings cause the waves (Houben, 1982) or do the waves cause the markings (Covey and Schubert, 1981), and if so, how?

Some partial answers are available. Of the absorbing constituents suggested before the Pioneer Venus mission, solid sulfur was certainly the most popular (Hapke and Nelson, 1975; Young, 1977). This has, however, been ruled out by Pollack *et al.* (1979) and Tomasko *et al.* (1979), who showed that orthorhombic sulfur could not be identified with any of the particles observed *in situ* by the Pioneer Venus cloud particle size spectrometer (Knollenberg and Hunten, 1979) without contradicting the known spectral reflectivity of the planet or the observed net radiative flux in the atmosphere.

At the same time (coincident with the beginning of the Pioneer Venus mission) sulfur dioxide was found in the Venus atmosphere from the ground (Barker, 1979), Pioneer Venus uv spectroscopy (Stewart *et al.*, 1979), IUE (Conway *et al.*, 1979), and *in situ* gas chromatography (Oyama *et al.*, 1980). Pollack *et al.* (1979) successfully matched the Venus spectral reflectance over a range of wavelength using the SO_2 distribution found by Esposito *et al.* (1979). Although it appeared that SO_2 might be *the* uv absorber, later work by Esposito (Paper I) and Pollack *et al.* (1980) showed that SO_2 was insufficient to explain the contrast seen at wavelengths longer than 3200 Å. Nevertheless, both the contrasts and the Venus reflectivity can be matched by SO_2 alone at shorter wavelengths. Further, the SO_2 amount predicts the location and darkness of features seen at wavelengths where SO_2 is only weakly absorbing. For simultaneous data collected over three Venus years, we find that the correlation between contrast at 3650 and 2700 Å is 0.74. Even though at least one additional absorber is required, a common cause for the uv contrast at all wavelengths is thus indicated. Sulfur dioxide provides a good analog for all the uv absorbers; models explaining the uv contrasts must minimally explain the observed SO_2 distribution.

Unfortunately, much more work remains to be done in this area. We have taken on a more limited task: to measure differences in the polarization of bright and dark areas on Venus; to match the differential polarization by simple models in which we vary the cloud height, amount of submicron haze above the clouds, and absorber amount in the clouds; and to propose physical and chemical models consistent with our findings.

THE VALUE OF POLARIZATION STUDIES

Polarimetry of the Venus clouds has several distinct advantages relative to other

studies. The observed polarization of scattered sunlight arises mostly from photons that have been scattered only once. The collective effects of multiple scattering of sunlight are minimized, and the observed polarization is thus characteristic of the properties of individual scatterers. Also, the region in which the polarization is formed is very restricted in altitude. Contributions come mostly from at and above the height at which the overlying atmosphere has an optical depth of unity. This is the same region visible to external viewers of the planet; correspondingly, the altitude region where the optical depth $\tau \cong 1$ is termed the "cloud top."

A second important advantage is that the variation of polarization with phase angle is strongly indicative of the size, shape, and refractive index of the scatterers. The further variation of polarization with wavelength gives another effective method of inferring the individual properties of the scatterers from remote observations. For Venus, the polarimetric analysis of ground-based observations by Hansen and Arking (1971) and Hansen and Hovenier (1974) led to the determination that the main Venus cloud is composed of a single size of spheres (~ 1 μm in radius) of concentrated sulfuric acid (Sill, 1972; Young, 1973). Later, Kawabata *et al.* (1980) used Pioneer Venus data from the cloud photopolarimeter experiment (Travis *et al.*, 1979a) to deduce the properties of the haze particles present over the Venus poles. Kawabata found the effective radius of these particles $r_{\text{eff}} = 0.23 \pm 0.04$ μm, the effective variance $v_{\text{eff}} = 0.18 \pm 0.10$, and the refractive index $n_r = 1.45 \pm 0.04$. These results allow the possibility that the submicron haze is also composed of sulfuric acid droplets. Conversely, Mukai and Mukai (1981) have shown that the model of Kawabata *et al.* (1980) is inconsistent with infrared observations. This casts doubt on the haze composition being purely H_2SO_4, as a strong absorber is required at 3.4 μm. The effect of such impurities in the visible is unknown, but the haze is clearly not absorbing at our wavelengths of observation. In what follows, we will assume a sulfuric acid composition.

Given the capability to deduce physical properties from the polarization, it was natural to seek to observe polarization differences between the bright and dark areas on Venus. Several attempts were made from the ground (Fountain, 1974; Coffeen and Hansen, 1974; Coffeen and Barker, 1973; Bowell, 1974) and from Mariner 10 (Hapke, 1974, 1976). These measurements do not allow any consistent interpretation; in fact, data taken on the same night by different observers show opposite results [for a review, see Travis (1975)]. Kawabata *et al.* (1980) report no observed correlation between brightness and polarization anomalies at low and middle latitudes. Esposito (Paper I) found a marginally significant positive correlation between contrast in the uv and polarization at 2700 and 3650 Å. However, these results could be explained without requiring any differential composition: the darker areas were more polarized simply because they were darker (and thus having a larger ratio of single- to multiple-scattered photons). From the scatter in the data of Paper I, it is easy to understand why the sparse ground-based and Mariner 10 data are somewhat inconsistent.

Given this large variability and the ensuing marginal significance of our previous findings, we have relentlessly continued to collect data on both the contrast and polarization of Venus as described in Paper I. The observations are taken on a regular schedule by co-aligning the Pioneer Venus ultraviolet spectrometer (UVS) and cloud photopolarimeter (CPP) to observe Venus simultaneously. The two instruments then provide coincident images of Venus at seven discrete wavelengths from 1980 to 9350 Å. At the four CPP wavelengths 2700 Å(U), 3650 Å(B), 5500 Å(G), and 9350 Å(R) we also measure the polarization magnitude and direction. The three UVS wavelengths are selected by a regular rotation among six

wavelengths, giving a total of ten wavelengths where we possess substantial data concerning brightness contrasts. The wavelength-dependent brightness data will be published elsewhere. In this paper we will examine only the observed correlations between contrast and polarization at the four CPP wavelengths. The data represent 27 coincident observations spread over the first 600 orbits (2½ Venus years) of the Pioneer Venus mission.

The method of finding the contrasted points and measuring the contrast and polarization is given in Paper I. The most obvious region which is noticeably darker than its surroundings is selected as the "dark" point. To minimize limb-darkening effects, the brightest point along the same meridian of longitude is selected for the "bright" point. This procedure is comparable to that used by ground-based observers, e.g., Coffeen (1971). In Paper I the observed polarization was plotted against the brightness contrast between the "bright" and "dark" points. The scatter in the data was large enough to make strong conclusions impossible. This scatter cannot be explained by observational error: the accuracy of the polarization measurement is better than 0.2% at all wavelengths, except at 2700 Å, where the accuracy is 0.5%.

As the Pioneer Venus mission progressed, the data set for this study grew. This allowed us to consider the additional variable of phase angle. Since the polarization is strongly dependent on the phase angle of observation, we hoped this could explain some of the scatter in our correlation plots. In fact, when we compare the polarization of the "bright" and "dark" uv points against phase angle, a significant difference is apparent. In Table I and Fig. 1 we present the polarization at the bright and dark 2700-Å features. Only at 5500 Å (Fig. 1c) do we see no difference between the polarization of the bright and dark ultraviolet areas.

Some conclusions are evident from these data. First, the polarization cannot be explained as merely the result of darkening. Paper I called this the "null" model, since the data were consistent with providing no new information. Two pieces of information contradict the "null" model. At 3650 Å between phase angles of 60 and 100°, the dark regions have positive polarization and the bright regions negative. Clearly, this cannot be explained by differences in the relative amount of multiple scattering. At 9350 Å we see differential polarization despite the fact that brightness contrasts are less than 5% at this wavelength. Lacking any difference in brightness, this polarization difference must be due to the differential distribution of some polarizing scatterer and not merely to uv absorption.

Since Rayleigh scattering by gas at 9350 Å is quite insignificant, the most obvious choice for a polarizing absorber differentially distributed between light and dark areas is the submicron haze seen by the CPP. In fact, Pollack *et al.* (1980) have proposed that variation in the amount of overlying haze is the dominant cause of the observed contrasts. At first glance the 9350-Å data support this model: the polarization is consistent with more submicron aerosols above the bright features. However, we must consider the question of quantity. Pollack *et al.* (1980) require an excess in the amount of overlying haze $\Delta\tau_h \sim 1$ over the bright regions to reproduce the observed contrasts. This change in haze amount should produce a much larger polarization difference at 9350 Å than is observed and, in fact, a large differential also at 5500 Å. The lack of any observable difference at 5500 Å argues for $\Delta\tau_h \leq 0.1$. (We will quantify this result in the next section.) Thus, although the polarization difference is evidence for excess haze above the bright features, the effect of this on the brightness is not sufficient to explain the observed uv contrasts.

Large changes in cloud top altitude between the dark and bright features were ruled out in Paper I. Hapke (1976) has also failed to find any discernible height differences in the Mariner 10 photographs of the

TABLE I

OBSERVED POLARIZATION (%)

Orbit number	Phase angle (°)	Bright region (Å)				Dark region (Å)			
		2700	3650	5500	9350	2700	3650	5500	9350
31	64	+5.0	−0.3	−1.2	−1.3	+6.6	+0.4	−1.1	−1.7
67	34	+1.3	−1.5	−1.5	−1.2	+0.9	−1.0	−1.0	−1.7
75	39	+1.7	−1.0	−1.4	−1.4	+2.5	−0.5	−1.1	−1.8
91	62	+4.5	−0.7	−1.2	−1.5	+7.1	+0.5	−1.3	−2.0
93	65	+3.4	−0.8	−1.1	−1.4	+6.1	+1.1	−0.6	−1.6
99	77	+5.1	−0.5	−0.8	−0.8	+8.2	+1.3	−0.8	−1.4
101	80	+4.3	−1.0	−1.1	−1.0	+13.9	+3.2	−0.8	−2.0
107	89	+4.7	−1.3	−1.3	−0.4	+7.4	+0.6	−1.0	−1.8
109	92	+3.5	−1.6	−1.3	−0.3	+9.4	+1.3	−0.7	−1.4
115	97	+2.0	−2.0	−1.0	+0.6	+7.0	−0.2	−1.3	−1.6
123	110	+0.8	−3.0	−1.5	+0.5	+3.5	−2.2	−1.8	−1.9
125	113	+0.2	−3.1	−1.5	+1.2	+1.3	−2.7	−0.8	−1.5
131	120	−1.2	−3.3	−0.9	−0.4	−0.7	−2.9	−1.6	−1.9
338	94	+5.1	−1.1	−1.5	−1.2	+11.3	+2.5	−0.6	−2.0
345	104	+3.2	−3.6	−1.3	−1.0	+9.8	+0.8	−1.4	−2.4
352	115	+0.9	−2.7	−1.1	−0.4	+1.5	−2.1	−1.7	−1.9
366	133	−2.7	−3.5	−0.8	−0.4	−2.1	−3.4	−1.4	−2.1
499	48	+5.0	+0.8	−1.3	−0.6	+6.0	+1.0	−0.7	−1.5
513	33	+1.4	+0.2	−0.6	−1.4	+2.6	+0.7	−0.7	−1.4
520	32	+1.1	+0.9	−0.8	−1.5	+2.4	+0.5	−0.8	−1.4
527	38	+1.6	+0.8	−1.0	−1.8	+2.7	+0.2	−0.7	−1.4
534	55	+5.1	−0.3	−1.4	−2.4	+6.2	+1.8	−0.6	−1.5
541	64	+4.5	−0.4	−1.2	−1.7	+8.4	+1.4	−0.9	−1.9
548	73	+5.1	−0.6	−1.1	−1.2	+8.1	+1.0	−1.0	−1.7
555	83	+9.7	+1.0	−1.1	−1.8	+7.8	+0.3	−1.2	−1.8
562	92	+3.3	−1.9	−1.4	−0.8	+8.7	+0.3	−1.3	−2.0
590	132	−2.0	−1.3	+0.7	−0.9	−1.3	−0.9	−0.8	−2.9

Venus limb. Travis (1975) showed that height differences alone were a totally unsatisfactory explanation for the contrasts. The present data set supports these conclusions in that polarization differences persist at 9350 Å. However, the question remains whether height differences are *associated* with the differences in brightness. This and other questions can only be answered by a more detailed analysis.

CALCULATIONS OF POLARIZATION FOR VENUS CLOUD TOP MODELS

The above discussion seems to rule out any simple explanation as the sole cause for the Venus uv contrasts. The model of Paper I, where contrasts are due to variation in the effectiveness of vertical mixing, cannot match our data. Likewise, models only incorporating altitude or haze differences are unsatisfactory. It thus seems that none of these is the proximate physical cause of the contrast, but rather that all contribute to (or at least are associated with) the actual mechanism responsible for the uv contrasts. We therefore consider quantitative models where several characteristics of the cloud top region vary, and compare these with the differences in polarization seen in our data.

The number of possible parameters in even a simple model of the Venus cloud tops is quite large (see, e.g., Kawabata *et al.*, 1982), and it is not our purpose to do an exhaustive study. Further, the amount and quality of our data are clearly insufficient to

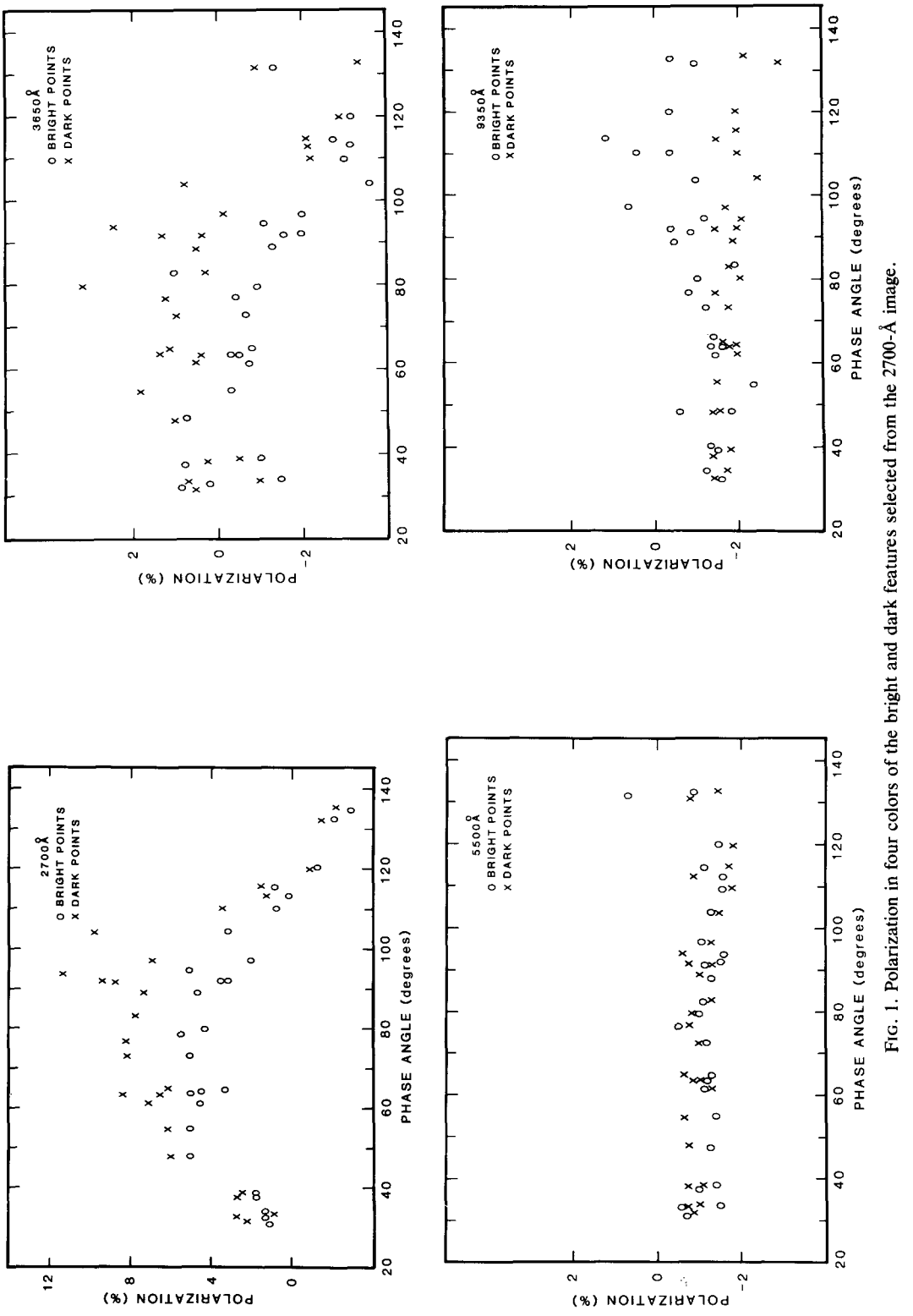

FIG. 1. Polarization in four colors of the bright and dark features selected from the 2700-Å image.

achieve the results characteristic of Kawabata *et al.* (1980, 1982). We pose for ourselves a more limited objective. We take as given the properties of the main cloud layer (Hansen and Hovenier, 1974), the submicron haze (Kawabata *et al.*, 1980), and the vertical distribution of the uv absorbers (Esposito *et al.*, 1979; Esposito, 1980). Our quantitative analysis will vary only four parameters: the amount of overlying haze τ_h (bright) and τ_h (dark), and the amount of Rayleigh scattering gas τ_R (bright) and τ_R (dark) above the clouds. In fact, we are most interested in $\Delta\tau_h = \tau_h$ (bright) $- \tau_h$ (dark) and $\Delta\tau_R$. The latter can be expressed in terms of pressure or altitude changes at the cloud tops.

The general procedure for the detailed modeling will be as follows. We determine τ_h by matching the polarization at 9350 Å, where τ_R is not significant in affecting the observations. Given the results for τ_h, we then match the observations at 2700 Å by varying τ_R. The curves at 3650 and 5500 Å serve as a check on our results. We take the simplest possible model for the vertical structure of the atmosphere. A thick layer of 1-μm aerosols (the main cloud) is overlain by a layer of haze aerosols and a layer of pure Rayleigh-scattering CO_2. The only intermixing of these layers is that the main cloud layer is mixed uniformly with CO_2 gas so that 0.035 of the extinction coefficient in the main cloud is due to Rayleigh scattering at 3650 Å. Neither the cloud and haze aerosols nor the haze and Rayleigh scatterers overlap. This model certainly does not represent the likely structure of the cloud top regions, but we expect that our quantitative results will approximate the relative amounts of each of the scattering constituents in the top optical depth of the Venus atmosphere. For example, see the analysis of Kawabata *et al.* (1980). In their Fig. 16, they match the polarization at 9350 Å over most of the disk with three different vertical distributions of haze (their model I corresponds to the model used in this work). All three give to within ±5% the same amount of haze above $\tau = 1$. For our models the polarization is calculated including multiple scattering and vertical inhomogeneity by a "doubling-adding" code (Hansen and Travis, 1974) run on the LASP VAX 11/780 computer system at the University of Colorado.

The results for 9350 Å are shown in Fig. 2. The smooth curves represent the disk-integrated polarization for the best-fitting models to the bright and dark data. The model parameters are given in Tables II and III. We have two reasons for using the disk-integrated polarization. First, it gives a smooth curve that is easy to follow as the polarization changes due to varying the model parameters. Second, because of the fact that the data were taken over a several year period, for a given phase angle the points represent a range of viewing geometry. Rather than have the model curves be multivalued, we use the disk integration as an average for sets of points taken at the same phase angle but at different times and viewing conditions. Since the locations of bright and dark points are broadly distributed over the visual disk of Venus (see Fig. 1 of Paper I), the disk integration is a reasonable averaging procedure.

For haze aerosols with size 0.23μm our result is $\Delta\tau_h = 0.03$ at 9350 Å. From Mie-scattering calculations we can calculate the scattering efficiency of these aerosols in the uv. We have τ_h (2700 Å)/τ_h (9350 Å) = 3.9, giving $\Delta\tau_h \approx 0.1$ at 2700 Å. Combining this result with the model for the main cloud of Hansen and Hovenier (1974) we can determine the best values for τ_R. In Fig. 3, we plot our results. We find $\Delta\tau_R$ (2700) = 0.011. As a check on our analysis and determination of $\Delta\tau_R$ and $\Delta\tau_h$ we plot the polarization observed from these cloud top models against the data at 3650 and 5500 Å.

Figure 4 shows this comparison at 3650 Å. No free parameters are involved: the model is totally determined by the 2700- and 9350-Å data. Although the shape of the polarization is matched by the model curves, the absolute difference between the

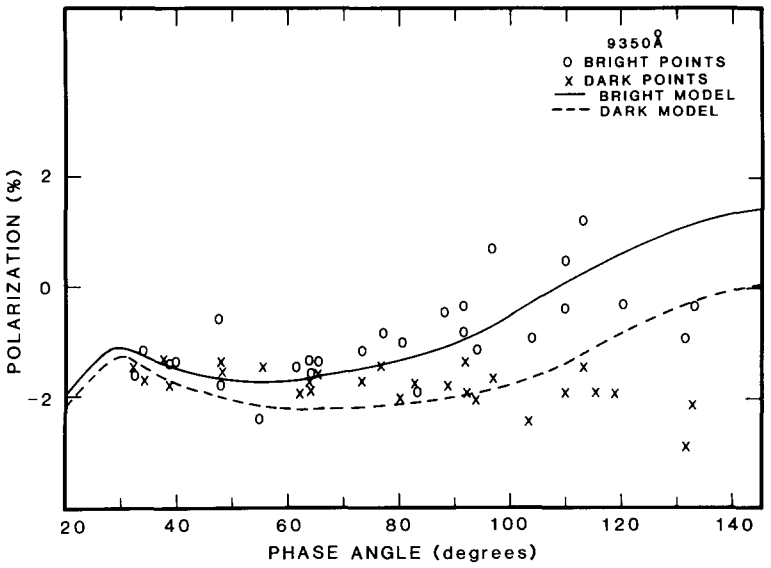

FIG. 2. Predicted polarization for the bright and dark uv features at 9350 Å. Model parameters are given in Tables II and III.

bright and dark areas is somewhat underestimated. Nonetheless, we consider the fit satisfactory given the lack of free parameters. We note in Fig. 4 the phase angle of Hapke's observations from Mariner 10. In agreement with his results, our model predicts that the brighter areas are more highly polarized than the dark areas.

At 5500 Å the situation is similar to that at 3650 Å (see Fig. 5). Although the fit is not perfect, the models are satisfactory; further, the predicted difference between the bright and dark features is small enough to be hidden in the noise of the data. Overall, we interpret the comparisons in Figs. 2–5 as a satisfactory fit to the eight phase

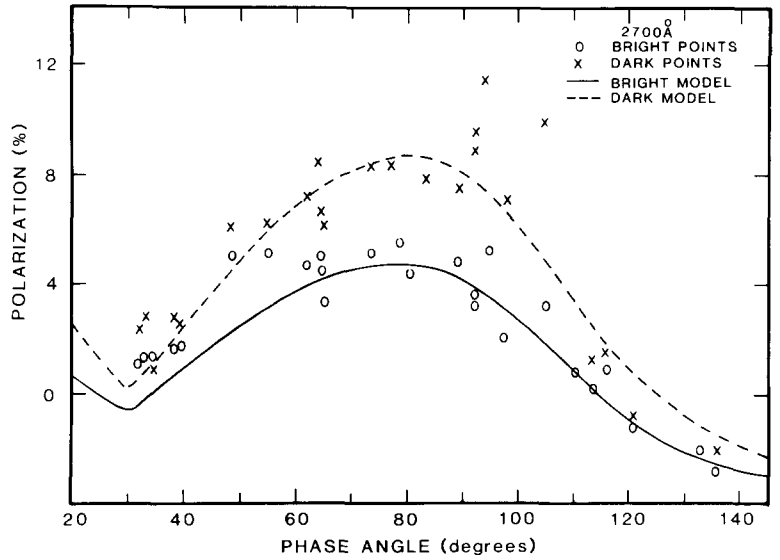

FIG. 3. Same as Fig. 2, but for 2700 Å.

TABLE II

MODEL PARAMETERS FOR BRIGHT ULTRAVIOLET FEATURES

	2700 Å	3650 Å	5500 Å	9350 Å
Clear gas layer				
Pressure at bottom: 5 mbar				
Optical depth	0.014	0.004	0.0008	0.0
Single-scattering albedo: 1.000				
Submicron haze layer				
Particle shape: spherical				
Particle size distribution: gamma function[a]				
Effective radius: 0.23 μm				
Effective variance: 0.18				
Composition: sulfuric acid				
Refractive index	1.49	1.46	1.44	1.43
Percentage contribution due to Rayleigh scattering: 0.0				
Total optical depth	0.39	0.39	0.27	0.10
Single-scattering albedo[b]	0.982	0.981	0.999	0.9993
Main cloud layer				
Particle shape: spherical				
Particle size distribution: gamma function[a]				
Effective radius: 1.05 μm				
Effective variance: 0.07				
Composition: sulfuric acid				
Refractive index	1.49	1.46	1.44	1.43
Percentage contribution due to Rayleigh scattering	0.11	0.034	0.0	0.0
Total optical depth: 20.0				
Single-scattering albedo[b]	0.982	0.981	0.999	0.9993

[a] See Hansen and Travis (1974).

[b] Selected to match Venus spectral reflectivity. See Kawabata and Hansen (1975).

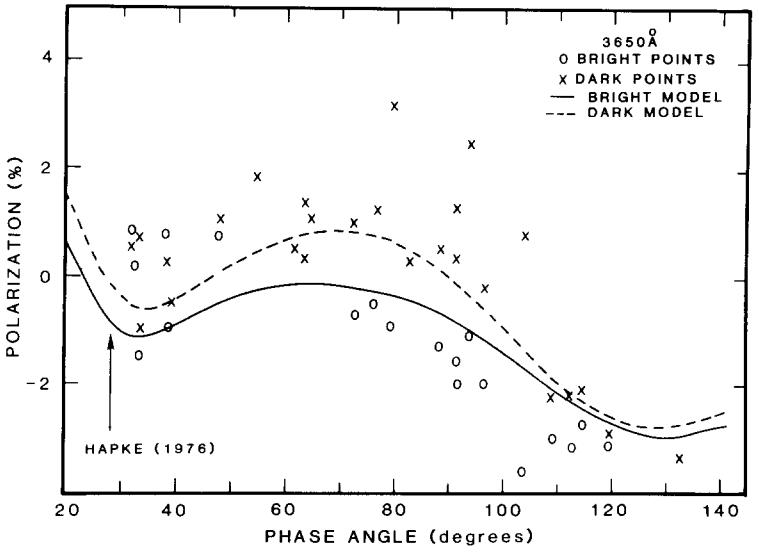

FIG. 4. Same as Fig. 2, but for 3650 Å.

TABLE III

MODEL PARAMETERS FOR DARK ULTRAVIOLET FEATURES

	2700 Å	3650 Å	5500 Å	9350 Å
Clear gas layer				
Pressure at bottom: 8 mbar				
Optical depth	0.025	0.007	0.001	0.0
Single-scattering albedo: 1.000				
Submicron haze layer				
All values the same as in Table I, except				
Total optical depth	0.27	0.27	0.19	0.07
Main cloud layer				
All particle parameters the same as in Table I				
Upper cloud layer[a]				
Total optical depth	1.25	1.25	—	—
Single-scattering albedo	0.975	0.975	—	—
Lower cloud layer[a]				
Total optical depth	20.0	20.0	—	—
Single-scattering albedo	0.953	0.953	—	—
Single cloud layer				
Total optical depth	—	—	20.0	20.0
Single-scattering albedo	—	—	0.999	0.9993

[a] This two-layer structure provides an approximation to the steep vertical gradient in absorber concentration. See Paper I.

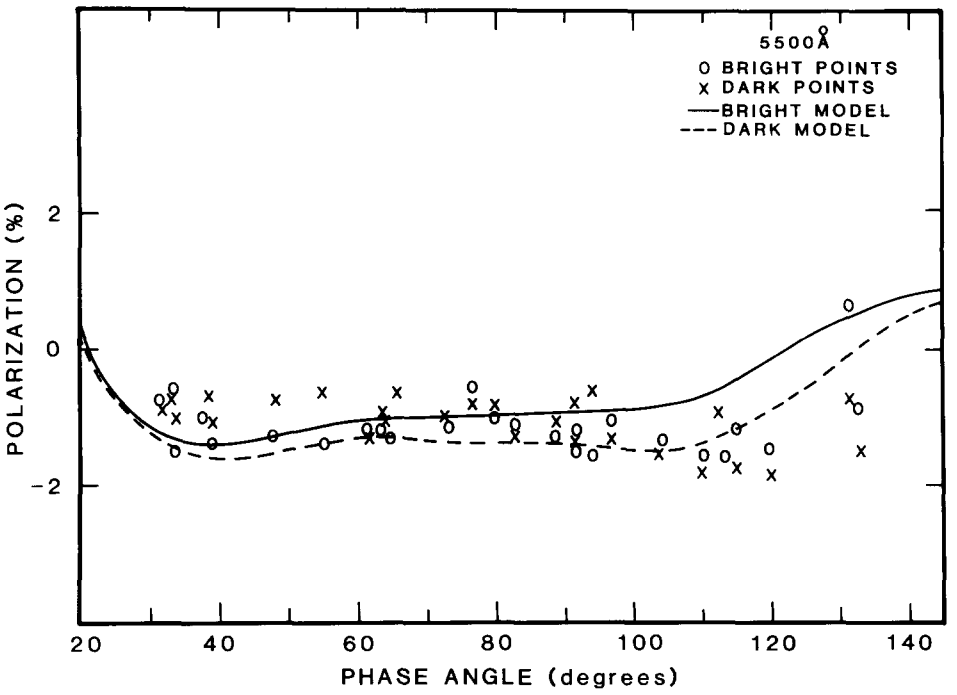

FIG. 5. Same as Fig. 2, but for 5500 Å.

curves using four free parameters. A better fit would certainly be possible with more free parameters, but this is not the goal of our modeling.

We varied the parameters about the values quoted above to estimate plausible error bars. We judged the fits by eye; all satisfactory appearing fits are within our error bars. Our strongest result is from the lack of any apparent differential polarization at 5500 Å. This gives $\Delta\tau_h$ (5500) < 0.10. Referred to the optical depths at 9350 Å this implies $\Delta\tau_h$ (9350) < 0.04. From the data at 9350 Å, we can conclude $\Delta\tau_h$ (9350) $= 0.03 \pm 0.02$. At the shortest wavelength (2700 Å) our data show $0.02 \leq \tau_R$ (dark) ≤ 0.03 (see Fig. 6). Similarly, we find τ_R (bright) $= 0.014 \pm 0.005$. From the magnitude of the difference in polarization, we conclude $\Delta\tau_R = 0.010 \pm 0.005$.

The amount of Rayleigh scattering at 2700 Å allows us to infer the cloud heights in the dark and bright uv regions on Venus. Following Kawabata *et al.* (1980), we define the cloud top as the pressure level where the optical depth due to clouds, hazes, and CO_2 reaches unity at 3650 Å. For our model of the vertical structure we have, for the cloud top pressure,

$$P \text{ (bright)} = 29 \text{ mbar},$$
$$P \text{ (dark)} = 37 \text{ mbar}. \quad (1)$$

This implies a height difference of 1200 ± 600 m. If, instead, we define the "main cloud top" as the pressure where the opacity in 1-μm H_2SO_4 aerosols and CO_2 reaches $\tau = 1$, then we have

$$P \text{ (bright)} = 40 \text{ mbar [main cloud]},$$
$$P \text{ (dark)} = 43 \text{ mbar [main cloud]}. \quad (2)$$

These results may be compared with Hapke's (1976) measurements of variations in the altitude of the limb from Mariner 10 images. He found no significant differences in the limb altitude to a limit of 600 m over features as large as 100 km. The bright and dark regions in our data are often separated

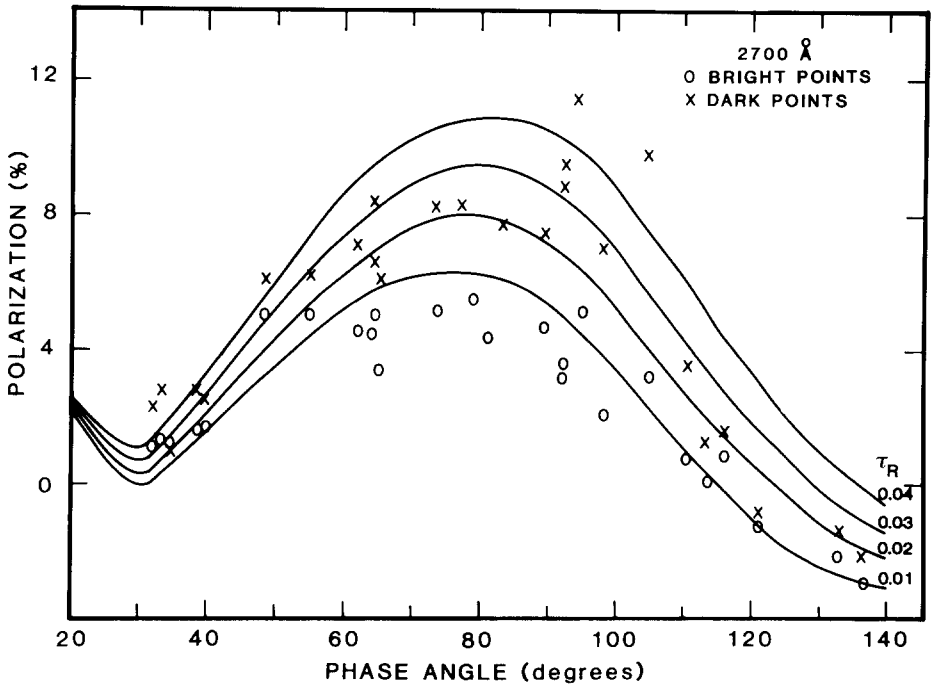

FIG. 6. Effect on predicted dark uv feature polarization of varying the amount of Rayleigh scattering above the aerosols.

by thousands of kilometers. In addition, the polarimetry is sensitive to all the scatterers above about 68 km, whereas the planet's limb is located at about 80 km; thus these results are not directly comparable. At the worst, however, the conclusions are marginally consistent. The temperature drop in 1 km is ~2°K: this is not large enough to be detected by differences in the rotational temperature of CO_2, consistent with the result of Young (1975).

This study has taken the individual aerosol properties as given. However, we can still ask whether another aerosol distribution could also yield a satisfactory fit to our data. For example, Kawabata *et al.* (1982) analyze the aerosols lying over the equator (2°S < latitude < 2°N) and find a mean size of 0.49 μm for the haze. Since the contrasts we are studying are broadly distributed through the latitudes ±60° (see Paper I), might not these particle properties be a more natural choice for the haze layer than the properties of the polar haze from Kawabata *et al.* (1980)? Strangely enough, this is not the case. In Fig. 7 we plotted the data at 9350 Å against several models incorporating the aerosols described by Kawabata *et al.* (1982). Rayleigh scattering is unimportant, and clearly no amount of 0.49-μm haze can match the bright feature polarization. As suggested by Kawabata *et al.* (1982), these differences may be overstated. Both their and our analyses do not consider the possibility of a vertical gradient in particle size, which seems quite probable. If such a gradient exists, it is possible to explain the differences in inferred mean size as expressing an observational selection effect. This same effect could explain the worsening of our model fit at phase angles greater than 110°. Our analysis is not sophisticated enough to draw conclusions about the absolute amount of such 0.49-μm aerosols above the Venus clouds; however, the observed difference in polarization cannot be explained by the differential distribution of such aerosols.

PHYSICAL AND CHEMICAL IMPLICATIONS

We have seen that the differential polarization between dark and bright uv regions on Venus can be explained in terms of known constituents of the Venus atmosphere. Our results show an anticorrelation between uv absorption and submicron

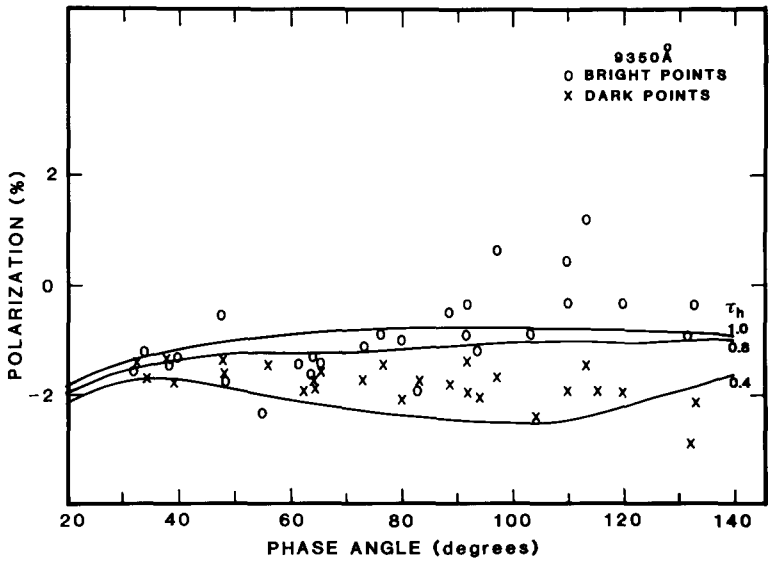

FIG. 7. Polarization predicted at 9350 Å for three values of τ_h for a distribution of ½-μm aerosols (r_{eff} = 0.49 μm, v_{eff} = 0.25; Kawabata *et al.*, 1982).

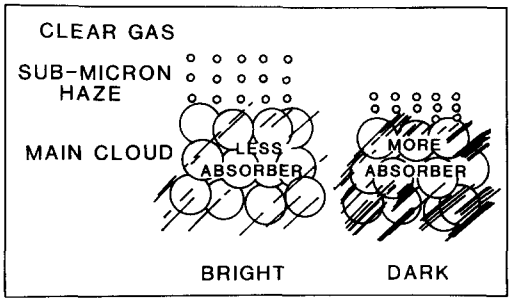

FIG. 8. Pictorial summary of our models for the atmospheric structure in the bright and dark uv features.

haze, and that the dark areas are slightly lower than the bright areas. Figure 8 summarizes our findings. These results have immediate implications for the possible causes of the uv contrasts and the chemistry and dynamics of the cloud top region.

First we note that the change in submicron haze and altitude is insufficient to explain the observed contrast in brightness. Pollack *et al.* (1980) calculate that to reproduce the observed contrast by haze alone requires $\Delta\tau_h$ (5500) $\gtrsim$ 0.6. This is greatly in excess of our upper limit $\Delta\tau_h$ (5500) $\leq$ 0.10. The effect of changing cloud height is negligible in creating brightness changes (e.g., Travis, 1975). Thus, we have not discovered *the* cause, but only processes which are associated with the underlying physical cause for the uv contrast.

We do know that the cause of the uv contrast cannot be as simple as the models proposed by Pollack *et al.* (1980) or Esposito (1980). The formation of dark features apparently requires (1) an increase in the amount of SO_2 and other absorbers (Paper I), (2) a decrease in the amount of overlying submicron haze (Pollack *et al.*, 1980; this work), and (3) a slight decrease in cloud height (this work).

We now wish to propose two plausible mechanisms which can explain our results. The first is a dynamical model. At the site of a dark uv feature we require a situation of vertical convergence and horizontal divergence (see Fig. 9). The cloud tops in this explanation serve as a barrier to vertical transport and as a location of rapid horizontal transport. Upwelling air brings with it an increase in the concentration of absorbers since their distribution shows a steep increase with depth (Esposito *et al.*, 1979; Pollack *et al.*, 1980; Paper I). Likewise, downwelling air brings a lower concentration of haze aerosols and clear gas down from above the altitude of photochemical production (e.g., Winick and Stewart, 1980). If the strong vertical shear in the zonal wind at about 60 km (Counselman *et al.*, 1980; Schubert *et al.*, 1980) extends to the cloud tops, this could transport the vertically converging air away from the location of enhanced absorption.

Conversely, the cause of the uv markings could be dominantly chemical. The observed anticorrelation between aerosol and absorber is basic to this explanation: at locales of high absorption we have less overlying haze and a lower main cloud. Since these two constituents are chemically related so that SO_2 is the source of the H_2SO_4

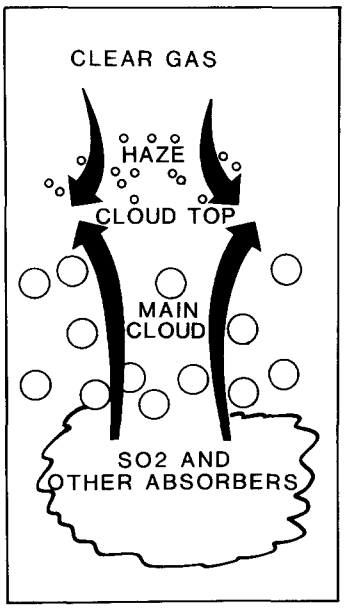

FIG. 9. Scenario of a dynamical explanation for the creation of the uv contrasts. See text for details.

and H_2SO_4 is the sink for SO_2, the anticorrelation may be interpreted as a conservation of sulfur amount. The variations in brightness then evidence the effectiveness of the conversion in the presence of sunlight. We propose that this conversion is sensitive to the local concentration of water vapor and molecular oxygen; in fact, one or both of these may be limiting.

Water vapor limits the oxidation of SO_2 to cloud aerosol by hydrating SO_3 to H_2SO_4, which is rapidly scavenged by existing acid droplets. An insufficiency of water will allow the SO_3 gas to be photolyzed back to SO_2 instead of being incorporated into existing aerosols. Molecular oxygen is important as a source of oxygen for the oxidation of SO_2. Although much of the necessary oxygen may come from SO_2 photolysis (Winick and Stewart, 1980), the production of aerosol will be considerably less in a region where O_2 is depleted.

Water vapor has long been known to be horizontally variable (e.g., Taylor, 1975) on Venus. This inhomogeneity provides a source for the observed horizontal brightness variation in the ultraviolet. The uneven distribution of O_2 has not been observed. Nonetheless, oxygen must have a very steep gradient near the cloud tops where it is consumed in the oxidation of SO_2 to acid aerosol: this is evident in the photochemical calculations of Yung and Demore (1982). Small uplifts, downdrafts, or mixing variations can easily perturb the equilibrium vertical distribution, leaving a locally depleted region.

Once a local depletion in water or oxygen arose it might persist for quite some time. The inferred time scales for vertical mixing at the cloud tops are on the order of months (Winick and Stewart, 1980). The regions where oxidation was limited would remain in their incompleted state of H_2SO_4 production until mixing restored equilibrium. Thus larger dark areas once created could be carried along with the cloud top wind velocity for many rotations. Consistent with observations, the largest features would have the longest lifetimes. Until new reactants were mixed in, the existing aerosols would continue to fall out, leading naturally to a lower main cloud altitude in the dark regions.

Strong support for this chemical hypothesis comes from an explicit calculation of sulfur abundance at the bright and dark regions. If the difference between bright and dark regions is only in the ability to oxidize and hydrate sulfur dioxide to sulfuric atoms, the number of sulfur atoms above the cloud tops should be conserved. That is, the excess SO_2 over the dark regions should represent the same amount of sulfur as the excess haze over the bright regions. From Esposito (1980), the amount of excess SO_2 required to explain the uv contrasts can be matched by an exponential distribution with a scale height of about 2 km and a mixing ratio at 40 mbar of 5×10^{-8}. This gives 1.2×10^{16} SO_2 molecules above 40 mbar in the dark regions. This is essentially the cloud top: see Eqs. (1) and (2). From the present work, the excess haze over the bright regions is $\Delta\tau_h$ (9350) = 0.03. This implies an excess column abundance, assuming pure H_2SO_4 haze with the particle size distribution given by Kawabata *et al.* (1980), of 1.3×10^{16} H_2SO_4 molecules. The spectroscopy and polarimetry are thus entirely consistent with conservation of sulfur atoms above the clouds; the varying chemical state of these atoms yields the observed brightness contrasts in the uv.

We note that if the contrasts are merely triggered by an imbalance in the chemistry near the cloud tops, the dark features may have almost no relation to planetary-scale dynamics. Although the larger features appear to be propagating slowly with respect to the mean zonal flow (Rossow *et al.*, 1980), it may be premature to interpret the periodic variations in brightness as planetary-scale waves (e.g., Covey and Schubert, 1981; Belton *et al.*, 1976b). Since we are still seeking the actual mechanism of contrast production, inferences drawn from the contrasts concerning dynamics must be treated with caution.

SUMMARY

The differences in polarization between bright and dark ultraviolet features on Venus have a straightforward interpretation in terms of known constituents of the atmosphere near the cloud tops. Our observations of the polarization in four colors over 2½ Venus years imply that the submicron haze and uv absorbers are anticorrelated, and that the clouds lie slightly (~1 km) lower in the dark regions. These findings pose strong constraints on any model for the brightness variations in the uv. All models that have been proposed to date are too simple to explain our observations. We suggest two plausible mechanisms consistent with our results. In the physical model, the dark uv features are locales of vertical convergence and horizontal divergence. In our chemical model, we suggest that the photochemistry is sensitive to local concentrations of molecular oxygen and water vapor. Where these are limiting we find a uv dark area characterized by high absorber concentration and low aerosol concentration. These portions of the atmosphere where the chemical state is in this extreme will persist because of the slowness of mixing near the cloud tops.

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